NUMERICAL INVESTIGATION OF THE WATER/ALUMINA NANOFLUID WITHIN A MICROCHANNEL WITH BAFFLES

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ABSTRACT

The study of heat transfer phenomenon in microchannels has attracted researchers' attention as they have many advantages in the cooling of electronic components. In this numerical study, the effect of adding alumina nanoparticles to the water flow through a microchannel with some baffles embedded on the top and bottom walls is discussed. The several cases including the effect of various volume fraction of nanoparticles (2, 4, 6, and 10%), Reynolds number of the inlet flow (10, 20, 30, 40, and 50), and the number of baffles and their heights on the heat transfer phenomena are investigated. The local Nusselt number, the average outlet temperature, and the streamlines are presented for representing the results. The results show that increasing the Reynolds number decreases the average outlet temperature. Moreover, the increase in the number of baffles causes an increase in the average outlet temperature since the formation of vorticities just behind of each baffle and results in a large heat transfer rate. As the baffles height increase, the strength and the area of the vortices increase and hence the heat transfer rate increases. However, an increase in the volume fraction of the nanoparticle increases the average outlet temperature which is due to the increase in conduction heat transfer of nanofluid.

KEYWORDS*: Microchannel, heat transfer rate, nanofluids.*

1.0 INTRODUCTION

Microchannels have many industrial and engineering applications including electronic cooling, medical industries, chemical engineering, automotive heat exchangers, laser equipment and aerospace technology. The microchannels were introduced firstly by Tuckerman and Pease (Tuckerman & Pease, 1981). Microchannels with liquid coolant like water are widely used to prevent overheating of electronic components and circuits. Therefore, the thermal management of microelectronics has become a promising field of research (Bar-Cohen, 2013; Colgan et al., 2007; Lee & Mudawar, 2009). The microchannels create a higher heat transfer surface per unit volume, as well as a higher heat transfer rate. However, the smaller size of the channel, the more pressure drop takes

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places on the flow. Higher pumping power is needed as a penalty of high inlet velocity occurs and significantly falls as hydraulic diameter increases (Sakanova et al., 2014). The study of heat transfer in microchannels using conventional liquids has been reported by many studies (Zhang et al., 2015; Lewis & Wang, 2018; Dixit & Ghosh, 2015). Basically, the heat transfer of the fluid flow is limited to their thermal properties. However, the methods of heat transfer augmentation in microchannels have been considered and introduced, recently. The most recent one is associated with the high thermal conductor nanoparticles suspended in base fluids and increase the thermal conductivity of the medium (Ganvir et al., 2017; Hajmohammadi et al., 2018; Chari & Kleinstreuer, 2018). These particles are generally metal, metal oxide or carbide with the diameters of 1-100 nm (Minkowycz et al., 2016).

Due to the very low flow rate, the microchannel flow is characterized by a very low Reynolds number. Therefore, it is difficult to achieve an effective turbulent flow. Manay and Shahin in 2016 investigated the effect of titanium oxide nanoparticles suspended in water on heat transfer in a microchannel. They concluded that increasing the volume fraction of nanoparticles and also decreasing the microchannel height would increase the heat transfer rate. Azizi et al. (2016) investigated the effects of water/copper nanofluid on the heat transfer rate and friction coefficient in a microchannel. They showed that by increasing the volume fraction of nanoparticles, the heat transfer rate increases. Moreover, the local Nusselt number and friction coefficient increase significantly by adding nanoparticles compared to the base fluid.

Alfaryjat et al. (2018) numerically studied the enhancement of heat transfer using various nanofluids in hexagonal microchannel as a heat sink. They separately examed three types of nanoparticles including aluminum oxide, copper oxide, and silicon oxide. They found that the aluminum oxide gives the highest heat transfer rate compared to the other nanoparticles. Ambreem and Kim (2018) studied the effect of nanoparticle size on the hydrothermal characteristics of nanofluids in a microchannel which is under a constant heat flux. They used water with aluminum and titanium oxide nanoparticles. The size of the nanoparticles was considered to be 20 to 200 nm. Eventually, they realized that the heat transfer rate increases by reducing the size of the nanoparticles. Reviewing previous studies leads us to conduct a study on the numerical simulation of two-dimensional flow and heat transfer of water-alumina nanofluid in microchannels using finite element method. The effect of various geometric parameters and flow conditions, including the different arrangement of the baffles, the height and the distance between them, the Reynolds number, and the volume fraction of nanoparticles, have been investigated.

2.0 THEORETICAL THEORY

Figure 1 shows the geometric configuration of the microchannel. The microchannel with the height L=1mm and a length of S =13L. The six baffles with the height of e1=0.5mm are embedded on the top and bottom walls. The distance between inlet and the first baffles on the top and bottom walls are the sb1 and sb2, respectively. The baffles are assumed to be adiabatic and with zero thickness in numerical simulation.

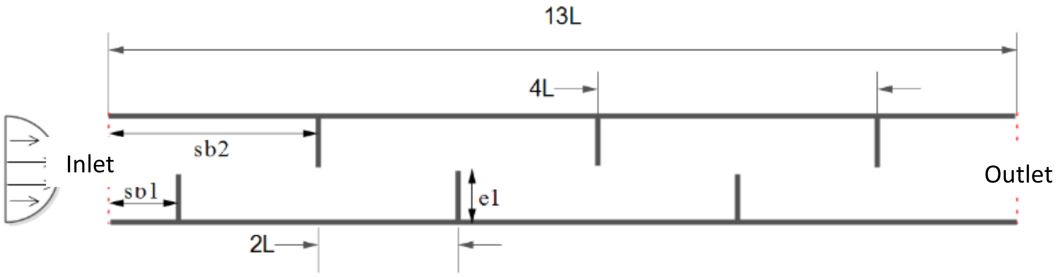

Figure 1. Schematic geometry of the microchannel.

The physical properties of the nanofluids are assumed to be constant and initially given at the inlet flow temperature. The flow is assumed to be laminar and steady. The inlet fluid flow is fully developed. Also, the wall temperature is uniform. Some physical properties of nanoparticles are shown in Table 1. The inlet fluid flow has the temperature of 21°C and the constant temperature of 57°C is assumed on the wall. Li et al. (2006) reported that the conventional Navier-Stokes and energy equations with no-slip boundary condition based on the continuum assumption are still valid and could precisely predict the fluid flow and the heat transfer characteristics in microchannels.

Table 1. Thermophysical properties of nanoparticles and base fluid at 27°C (Akbarinia et al., 2011).

Properties	**Water**	**Alumina**
Density (kg/m^3)	998.2	3890
Heat Capacity (J/kg K)	4240	880
Thermal Conductivity (W/m.K)	0.608	35
Diameter (nm)	--	36

The governing equations include the continuity, momentum, and energy equation;

$$\rho \nabla . u = 0 \quad (1)$$
$$\nabla . [-p + \mu(\nabla u) + (\nabla u)^T] = 0 \quad (2)$$
$$\rho C_{P.} \nabla T = \nabla . (k \nabla T) + Q \quad (3)$$

To calculate the density and thermal capacity of the water/alumina nanofluid, the following relationships are used:

$$\rho_{nf} = (1 - \emptyset)\rho_f + \emptyset \rho_P \quad (4)$$
$$(\rho C_P)_{nf} = (1 - \emptyset)(\rho C_P)_f + \emptyset(\rho C_P)_p \quad (5)$$

The equation 6 is used to calculate the viscosity of the nanofluid. This correlation is based on the experimental results of Meiga et al. (2004) for nanofluid of water/alumina.

$$\mu_{nf} = (1 + 2.5\emptyset + 150\emptyset^2)\mu_f \quad (6)$$

The thermal conductivity of the nanofluid is determined by Chein, & Huang in 2005. This relationship takes into account the effect of Brownian motion and the average diameter of nanoparticles, which is as follows:

$$\frac{k_{nf}}{k_f} = 1 + 64.7\, \emptyset^{0.7460} \left[\frac{d_f}{d_{np}}\right]^{0.3690} \left[\frac{k_p}{k_f}\right]^{0.7476} Pr^{0.9955} Re^{1.2321} \quad (7)$$

The special Reynolds number (Re) and Prandtle (Pr) are defined as:

$$Pr_f = \frac{\eta}{\rho_{f\ \alpha_f}}, Re_f = \frac{\rho_f K_B T}{3\pi\eta^2\lambda_f} \quad (8)$$

K_B is the Boltzmann constant equal to 1.3807×10^{-23} J/K and λ_f is the mean free path of the water molecule equal to 0.17 nm and η are also calculated by equation 6 :

$$\eta = A \times 10^{\frac{B}{T-C}},\ A=2.414\times10^{-5}, B=247.8, C=140 \quad (9)$$

The amount of heat absorbed by the fluid through the pipe is equal to the amount of heat that pass through the walls. Therefore, the method for calculating the heat transfer coefficient is as follows:

$$h = \left[\frac{\rho Q C_P (T_{out} - T_{in})}{A(T_{wall} - T)}\right] \quad (10)$$

The local Nusselt number on the walls of the microchannel calculated as follows.

$$Nusselt\ number = \frac{hL}{k_f} = \frac{q_W L}{(T_W - T_b)k_f} \quad (11)$$

3.0 RESULTS AND DISCUSSIONS

The set of equations of continuity and momentum and energy are discretized on the network including the triangular elements shown in the Figure 2. The numerical solution has been done with Ansys-Fluent software. To improve the accuracy of the solution, the mesh is refined in the vicinity of each baffle. To get accurate of numerical simulation a mesh study was accomplished by calculation the Nusselt number in the heated walls versus the number of grids. Finally, the network includes the number of 12531 cells have been selected for evaluating the results.

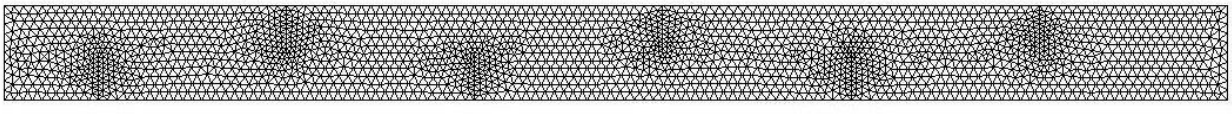

Figure 2. Networking of the model

To validate the numerical method, the local Nusselt number of the nanofluid flow with the Reynolds number of 6.9 and volume fraction of 5% was calculated and represented in Figure 3. The results were compromised with the data of Akbarinia et al. (2011) work. As it can be observed the results are in a good agreement with the laboratory data, so the numerical model would be suitable for the modelling of the problem.

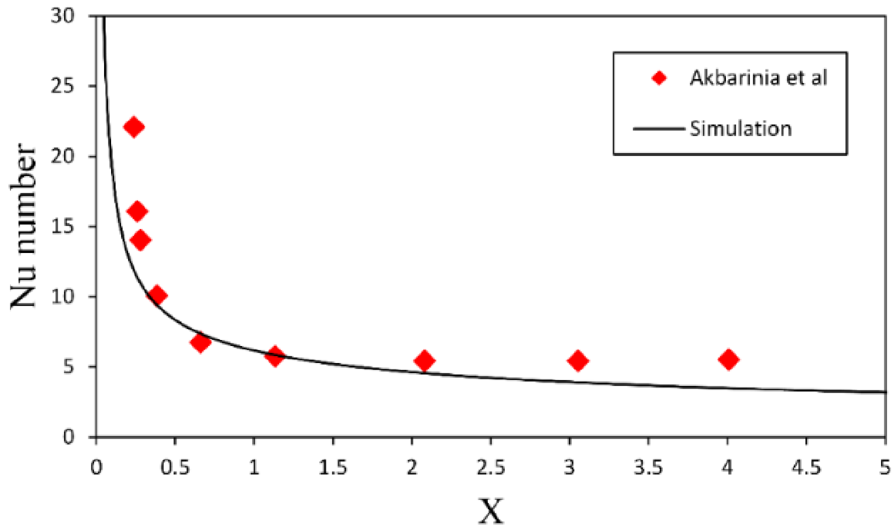

Figure 3. Comparison between the present results of Nusselt number and the data of Akbarnia et al. (2011).

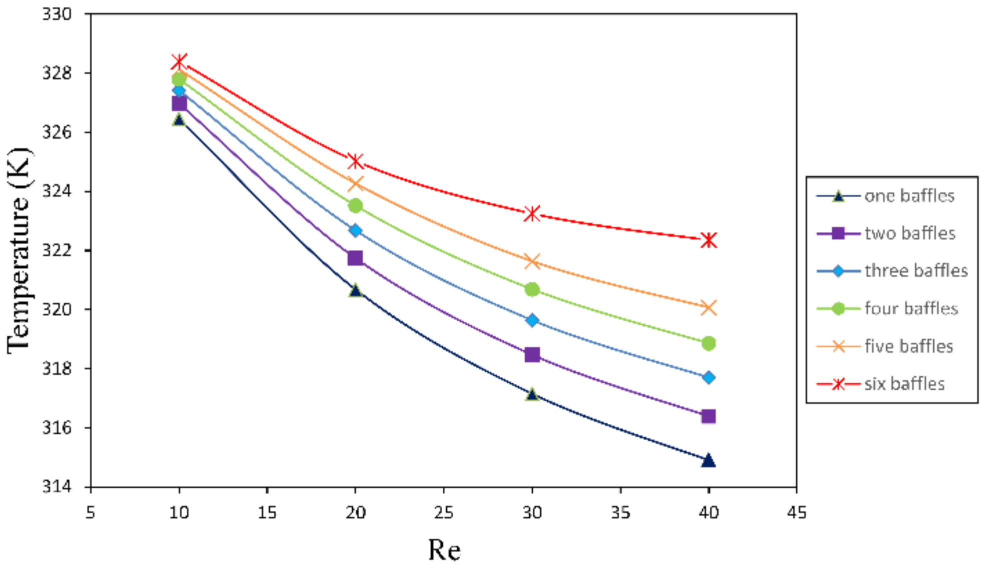

Figure 4. The average outlet temperature with various Reynolds and baffles number.

The effect of baffles on the flow pattern for various Reynolds numbers is shown in Figure 4. As the Reynolds number increases, the average outlet temperature decreases. For the microchannel of a single-baffle at the Reynolds of 10 and 40, the outlet temperature is equal to 326.45 K and 314.9 K, respectively. As the Reynolds number increases, the volumetric flow rate through the channel increases. Therefore, the convective heat transfer coefficient increases and the average outlet temperature decreases. The effect of the number of baffles on the average outlet temperature in various Reynolds number also depicts at Figure4. The greater the number of the baffles, the more the rejoin where the vortices form, which leads to an increase in the heat transfer. As it is observable, for Reynolds of 40, the outlet temperature changes from 315 for one baffle to about 322 for six baffles. The other point is that for the higher Reynolds number, the affection of the number of the baffles is more significant. The reason lays on the augmentation of the strength of vortices which are formed adjacent each of the baffles.

The local Nusselt number along the length of microchannel on the top and bottom wall is shown at the Figure 5. As it can be observed, the local Nusselt number fluctuates along the microchannel and the trend is downward. As the flow pass through the microchannel, the temperature difference between the nanofluid and the walls reduces; therefore, the local Nusselt gets decreases along the microchannel length. Since the first baffle is embedded on the top wall, the first pick is observed on the top local Nusselt number trend. The picks are located at the rejoin where the vortices are formed.

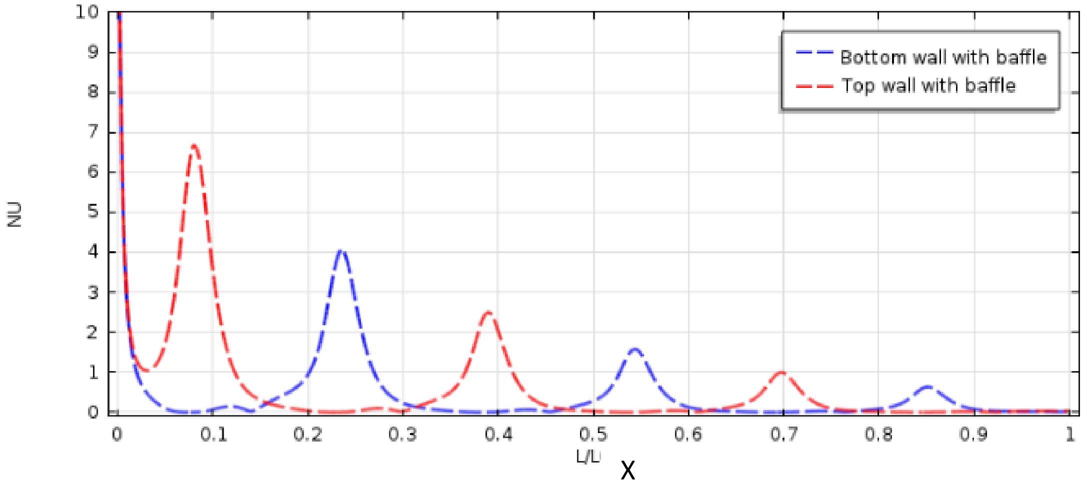

Figure 5. Local Nusselt number along the microchannel on the top and bottom walls for the case of six-baffles and Reynolds of 10.

The effect of baffles height including the 0.33 L, 0.5 L, and 0.5 L on the average outlet temperature, for various Reynolds numbers, in a three baffles involved microchannel, is provided at Figure 6. As the baffles height increases, the more strong vortices are generated becomes larger and so the more nanofluid gets stuck behind the baffle. Subsequently, the heat transfer between the wall and the nanofluid increases and the outlet temperature increases.

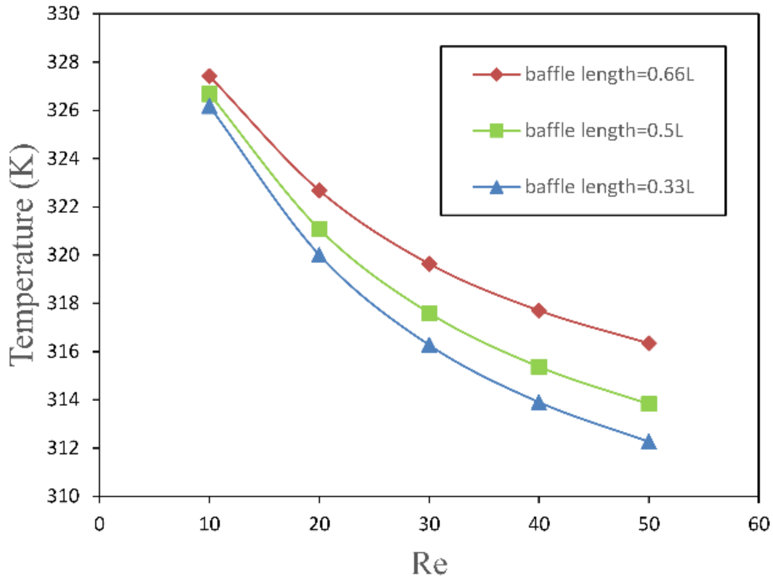

Figure 6. Average outlet temperature of the three-baffle involved microchannel for various Reynolds at different baffles height.

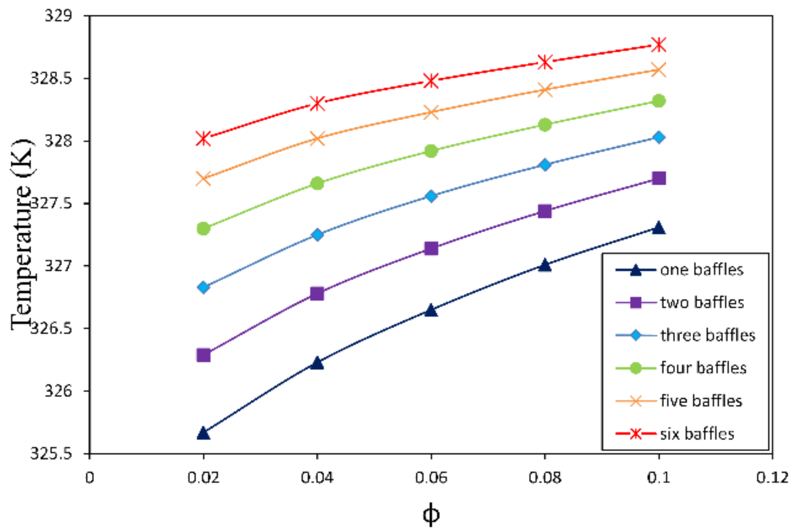

Figure 7. Shows the average output of microchannel with a volume fraction of different nanoparticles in the number of baffles in Re = 10.

The effect of addition of alumina nanoparticles to the heat transfer characteristics for various numbers of baffles is shown at Figure 7. As the volume fraction of nanoparticle increases from 0.02 to 0.1, the outlet average temperature of the microchannel output increases about 1 to 2 degree centigrade. Adding nanoparticles increases the conduction heat transfer coefficient as it was predicted by equation (7). When the nanofluid flows through the microchannel the both convection and conduction heat transfer play roles to convey heat from the walls to the nanofluid. Adjacent the walls, where the no-slip condition is applied, the conduction heat transfer is dominant; therefore, the nanoparticles with a higher heat conduction coefficient improve the heat transfer in this rejoin. However, near the microchannel center line, where the wall affection is negligible, the convection heat transfer plays the main role. For this, addition of nanoparticles to the base fluid results in the viscosity increasing (see equation 6) which in turn, reduces the strength of vortices circulation and the convective heat transfer. The decreasing in the slope of outlet average temperature versus the volume fraction is because of the affection of viscosity increment and its influence on the strength of vortices.

4.0 CONCLUSIONS

In this study, a numerical modelling of the heat transfer of nanofluids flow of water/alumina through a microchannel includes fins was investigated. The effect of numbers and height of the baffles, Reynolds number, and the volume fraction of nanoparticles in the nanofluid on the heat transfer characteristic were studied. The governing equations were solved by finite element method used by Ansys Fluent software. The results show that the increase in the number of baffles leads to an increase in the number of vortices, which augments the heat transfer between the nanofluid and the microchannel walls. The results also show that an increasing in the Reynolds number causes a decreasing in the microchannel average outlet temperature. As the height and number of the baffles increases, the extent of the nanofluid involved in the vortices zone increases and, subsequently; the heat transfer increases. Finally, it was observed that an increase in the volume fraction of nanoparticles increases the average outlet temperature as the result of the heat transfer conduction increase.

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